Effect of pasture type on regeneration of eucalypts in the woodland zone of south-eastern Australia

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Abstract: Although eucalypt regeneration is an uncommon event in the highly modified rural environments of south-eastern Australia, it still occurs on some roadsides and even in grazed paddocks. A number of observations suggest that under grazing, regeneration is more likely to occur in native pastures than in those dominated by exotics. The apparently adverse effect of exotic pastures was investigated by monitoring growth and survival of eucalypt seedlings — either planted or from sown seed — on the Central Western Slopes of NSW. Survival of seedlings arising from direct drilled seed of *Eucalyptus albens* and/or *Eucalyptus melliodora* in exotic pastures was generally low. However, survival was higher for seedlings emerging in spring (but not at other times) in an annual exotic pasture than for those emerging in spring in a perennial exotic (*Phalaris*) pasture. Experimental plantings of *Eucalyptus melliodora* seedlings adjacent to annual exotics v. a perennial native grass plant showed no significant difference in seedling growth between the two microsites though there was a trend towards enhanced survival near the perennial grass.

Within the context of other work on the regeneration of woodland eucalypts, these results suggest that: (1) competition from annual exotics is a major limitation to the survival of eucalypt seedlings in their first year; (2) competition from a perennial exotic establishing at the same time as the eucalypt seedlings is particularly severe during the eucalypt's second year. In the absence of a major disturbance such as scalping of topsoil, regeneration of eucalypts in exotic pastures is unlikely.

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Introduction

The subhumid zone of southern Australia has been intensively used for many years and modification of the original woodlands and forests ranges from relatively minor to complete. Areas of remnant woodland with intact ground-storey, however, are rare as noted, for example, by Prober and Thiele (1993) in the area originally occupied by grassy *Eucalyptus albens* woodlands. (Botanic nomenclature follows that of Harden (1990–93) and for grasses, Wheeler et al. (2002)). Due to widespread grazing ± cropping, ground-storeys are more appropriately considered as 'pastures': ranging from those still dominated by native perennial grasses ('native pastures') to those dominated by exotic annuals or perennials ('exotic pastures'). Introduction of exotic plants, as well as cultivation and grazing, were considered by Nadolny (1995) to be the main reasons for lack of eucalypt regeneration.

The pre-European settlement frequency and abundance of eucalypt recruitment in woodlands is speculative but was probably dependent on patchy fires and light grazing (Allcock et al. 1999) or canopy disturbance (Yates & Hobbs 1997) followed by suitable rainfall. Observations by Yates and Hobbs (1997) and Allcock et al. (1999) suggest that once woodland modification has reached the stage where the under-storey is dominated by exotics, eucalypt recruitment is unlikely. Apart from increased grazing intensity, other changes evident at this level of modification may include soil compaction, nutrient enrichment and reduced litter (Yates & Hobbs 1997, Windsor 2000).

Although natural recruitment is very rare in some areas e.g. the *Eucalyptus salmonophloia* woodlands in the wheatbelt of WA (Yates & Hobbs 1997), it still occurs along some south-eastern Australian roadsides as evidenced by remnant woodlands with mixed age structure (e.g. Schabel & Eldridge 2001). Whether recruitment in these situations is associated with the absence of grazing, intermittent heavy grazing or other disturbance is unclear.

Various authors have noted that eucalypt recruitment is more likely to occur in native rather than exotic pastures e.g. in the mid-north of South Australia (Venning 1985), northern tablelands of NSW (Curtis 1989, 1990) and the central west of NSW (Cluff & Semple 1994, Semple & Koen 2001). Initiation of recruitment in these cases was associated with some form of 'natural' disturbance e.g. light grazing, drought or fire. Recruitment can also occur in exotic pastures but, as noted in most of the documented cases (e.g. Whalley & Curtis 1991, MacLennan et al. 1992, Lawrence et al. 1998), only after a weed-free seedbed has been deliberately or accidentally prepared. This supports Yates and Hobbs' (1997) proposal that the transition from woodlands with exotic under-storeys to something resembling their original condition involves a major threshold, which cannot be crossed without considerable intervention.

These observations raise a number of questions. Assuming adequate seed supply and appropriate rainfall, why are native pastures apparently more conducive to eucalypt recruitment; or alternatively, why are exotic pastures not conducive to recruitment? A number of possible reasons have been suggested and some of these are addressed below.

Effects of individual species

In an experiment involving planting a native forb into artificial gaps in two perennial pasture types, Hitchmough et al. (1996) reported that competition from the native pasture (*Austrodanthonia setacea*) was less than from the exotic (*Festuca arundinacea*) one. Also, allelopathic effects may be produced by some species e.g. as reported in residues of the exotic perennial grass, *Phalaris aquatica* (Leigh et al. 1995).

Structure and composition of the pasture

The presence of tussocks themselves may affect eucalypt establishment. Following a fire in an *Eucalyptus pauciflora*–*Poa* sp. woodland in the Kosciusko area, Noble (1980) reported a significant interaction between the occurrence of two-year old eucalypt seedlings and grass tussocks. Seedlings were rare close to tussocks but most abundant 4–8 cm away. Compared to those in the 4–8 cm zone, seedlings further away tended to be shorter and had more stems. Results were attributed to competition close to the tussock, protection at 4–8 cm and exposure e.g. to frost, further away.

Curtis (1990) observed that burning native pastures produced suitable conditions for eucalypt recruitment but burning exotic pastures did not due to excessive growth of weeds. He also noted that bare ground was usually present between tussocks in native pastures but not in exotic ones where gaps were occupied by annuals. Simulated eucalypt seedfall experiments in exotic annual pastures with variously prepared seedbeds resulted in emergence, even in untreated controls, but survival was low except in the scalped treatment in most seasons (Semple & Koen 1997). Mortalities were attributed to competition from exotic annuals.

Fertility

As many native pastures in the subhumid zone are now restricted to infertile sites, e.g. with skeletal soils, it could be argued that low fertility rather than the presence of native pastures per se, is the issue; or conversely, that enhanced fertility is associated with the presence of exotic pastures and reduced eucalypt recruitment. [However, it should be noted that native pastures and fertile sites are not incompatible. On the NSW tablelands, for example, legumes have been introduced and fertilisers applied to pastures dominated by native grasses (Simpson & Langford 1996) though eucalypt recruitment has not been reported in these situations.] Venning (1985) reported that eucalypt recruitment was uncommon in fertilised paddocks but occurred in adjacent unfertilised ones. Cluff and Semple (1994) reported that eucalypt recruitment, initiated by an earlier fire, was absent from nutrient enriched sites ('sheep camps') within the same paddock.

Windsor (2000) argued that nutrient enrichment and soil compaction limited eucalypt recruitment on grazing lands. As evidence, she cited the success of scalping topsoil (to remove nutrients), followed by harrowing (to reduce compaction) in promoting eucalypt regeneration; but as noted by Lawrence et al. (1998), scalping also removes weed seeds and harrowing could provide safe sites for seeds on the otherwise smooth surface of a scalped soil. Allcock (2002), however, reported poor growth of *Eucalyptus albens* seedlings in the presence of exotic weeds in pot trials, particularly at high levels of phosphorus. Further, it is generally accepted that improving fertility e.g. by applications of fertiliser and/or lime, results in a decrease in woody plants and in increase in herbaceous ones as was as was reported in heathland by Heddle and Specht (1975).

Timing and intensity of grazing

With the exception of fertilised native pastures, most native pastures support lower numbers of livestock than equivalent areas of exotic pastures. Hence, it could be argued that low grazing intensity is responsible for higher eucalypt recruitment; or conversely, that high grazing intensity inhibits recruitment. Although exclusion of livestock and feral animals is generally considered a prerequisite for eucalypt regeneration (e.g. Venning 1988, Anon. 1992), recruitment can occur in native pastures under low grazing intensity (Venning 1985) or under intermittent heavy grazing (Curtis & Wright 1993).

A number of studies have indicated that heavy grazing may promote woody plant regeneration by opening up regeneration niches (Braunack & Walker 1985, Williams & Ashton 1987, Archer 1994) and if woody plants are unpalatable, that continued grazing may favour their survival. Grazing prior to eucalypt emergence, and possibly for some time afterwards (when seedlings are inconspicuous), may benefit eucalypt recruitment initially by creating bare ground and subsequently by removing annuals, which are generally grazed preferentially, at least by sheep (Wilson & Harrington 1984). More advanced seedlings, however, are preferentially browsed by some native and feral animals (Leigh & Holgate 1979, McIlroy 1984) as well as by domestic stock, at least during some periods of the year (Semple & Koen 2001). Some studies of fenced v. unfenced eucalypt seedlings have shown no differences in mortality, e.g. in *Eucalyptus incrassata* (Wellington & Noble 1985) and *Eucalyptus marginata* (Stoneman et al. 1994), where mortality was attributed primarily to water deficits and/or high summer temperatures. Other studies, however, have shown increased survival in exclosures, particularly after fire in the case of advanced ('lignotuberous') seedlings of *Eucalyptus pauciflora* (Leigh & Holgate 1979).

Deliberate attempts at initiating recruitment in woodlands by excluding livestock have generally been unsuccessful even when weed control was attempted. Exclosure and weed control around seven eucalypt trees of different species in SA resulted in recruitment in only one species, *Eucalyptus camaldulensis* (Venning 1988), though pasture type was not specified. A similar lack of response to exclosure and one application of herbicide occurred at two woodland sites with exotic pastures in the Bathurst area in the late 1980s (Semple, unpublished data). However, as noted previously, exclosure and particular attention to seedbed preparation in exotic pastures can result in recruitment in some years.

Despite these reservations, fencing native vegetation is a common conservation practice. Facilitating eucalypt recruitment may not be the primary aim of fencing but it is often assumed that it will occur. Spooner et al. (2002) investigated this hypothesis by comparing tree regeneration in areas that had been fenced for 2 to 4 years with adjacent unfenced areas in three native woodland types (two eucalypt and one pine) of southern NSW. Across the 47 paired sites, they found significantly more regeneration in the fenced areas. As sites were initially selected for fencing on the basis of 'relatively high quality', it can reasonably be assumed that ground-storeys were dominated by native grasses i.e. 'native pastures'. The authors claimed to be assessing post-fencing recruitment but its definition viz. saplings less than 3 m tall, suggests that this may not always have been the case. To achieve this height, growth rates would have to have been up to 75 cm/year (for 4 years of exclosure) or 150 cm/year (for 2 years of exclosure). Even the lower of these growth rates is comparable only to rates achieved from very successful cases of direct seeding (e.g. Semple and Koen 2001 Table 3) not what would be expected in the presence of uncontrolled herbaceous competition. It is therefore likely that some, and perhaps all, of the regeneration assessed was pre-fencing suppressed ('lignotuberous') seedlings/saplings rather than post-fencing recruitment.

This brief review supports the general notion that eucalypt recruitment is more likely to occur in native pastures than in exotic ones. However, the reasons for this are still unclear as factors such as fertility and grazing regime may interact with pasture composition/structure. Further, as noted by Venning (1988), recruitment processes may also differ between eucalypt species themselves.

In an attempt to shed some light on factors affecting recruitment in non-native pastures, three eucalypt seeding/planting experiments were carried out on in the Central Western Slopes botanic region in the late 1990s. Seedlings of local eucalypt species, *Eucalyptus melliodora* and/or *Eucalyptus albens*, were established either in situ from seed (direct seeding) or from tubestock, in seedbeds prepared by mowing and/or one or more applications of herbicide. Prior to sowing/planting, all sites were fenced to eliminate grazing by domestic and feral animals as a factor affecting seedling survival. Although these experiments did not involve natural recruitment, it was assumed that factors affecting growth and survival of eucalypt seedlings, whether naturally or artificially regenerated, would be similar.

Specific hypotheses being tested were: (1) Eucalypts can be established from seed in pastures dominated by the competitive exotic perennial, *Phalaris aquatica*, if it can be controlled during the critical first year of the eucalypt's life; (2) Spring is the optimal sowing time for eucalypt establishment in annual exotic pastures; (3) Survival/growth of eucalypt seedlings is higher when they are planted adjacent to a native grass than when planted within annual exotics.

Methods

Experiment A: Success of direct drilled eucalypt seed in a Phalaris-*dominant pasture treated with herbicide up to one year previously*

The experimental site at Walli (33° 40' 00" S, 148° 53' 20" E, 600 m a.s.l) was located on a low rise in an area originally supporting *Eucalyptus albens*. The site had been grazed for many years and fertility had been enhanced by applications of phosphate. *Phalaris aquatica*, *Trifolium* spp. and other exotic annuals dominated the pasture. Five seedbeds (treatments) were prepared using a single application of the non-selective herbicide glyphosate (15 mL/L water, applied with a knapsack) at either 12 months (September 1995), 10 months (November 1995), 6 months (March 1996), 3 months (June 1996) or 0 months prior to sowing. The area was mown regularly to simulate close grazing during this period. Glyphosate was also applied twice to all treatments in the two weeks prior to sowing in September 1996. (It was hoped that the duration of weed control achieved post-sowing would be directly proportional to the duration of weed control effort applied pre-sowing.) The five treatments were replicated five times as blocks.

Seed of *Eucalyptus albens* was sown in shallow furrows prepared with a small pick at the rate of 1 g (seed + chaff)/ 1.5 m row in four rows within each 2 m × 2 m plot. Seed was covered by a few millimetres of soil and pressed down by hand. Germination testing under a daily 20°C dark/ 30°C light regime for one month, indicated 256 live seeds/g (seed + chaff). Herbaceous vegetative cover of each plot was assessed by two throws of a 2 m × 0.5 m 100-point quadrat at regular intervals until May 1997. Eucalypt seedlings were counted in each row at regular intervals until May 1997 then less frequently until early February 1999.

Seedling counts and vegetative cover data were analysed using analysis of variance (ANOVA) methods (Genstat 5 Committee 1995). The repeated measures nature of the eucalypt seedling counts was addressed by analysing data at strategic time points, namely at the first time of observation and at the end of the summer seasons.

Experiment B: Success of direct drilled eucalypt seed sown monthly in an exotic annual pasture

The experimental site at Manildra (33° 10' 40" S, 148° 42' 50" E, 460 m a.s.l.) was located on a mid-slope with scattered *Eucalyptus albens*, *Eucalyptus melliodora* and *Eucalyptus microcarpa*. The site had been grazed for many years and fertility had been enhanced by occasional applications of phosphate. The pasture was dominated by exotic annuals with scattered perennial native grasses, especially *Bothriochloa decipiens*. Six months prior to the sowing trial described below, much of the biomass and scattered perennials were removed by mowing and applying glyphosate at 15 mL/L water using a knapsack.

The experiment comprised twelve treatments of monthly sowings, replicated three times as blocks. Each 3 m × 0.6 m plot was split into two 3 m long rows, which were randomly allocated to 1.5 g (seed + chaff) of either *Eucalyptus albens* or *Eucalyptus melliodora*. Germination testing under a daily 20° C dark/30° C light regime for one month, indicated 170 and 736 live seeds/g (seed + chaff) of *Eucalyptus albens* and *Eucalyptus melliodora* respectively.

Seedbed preparation was similar to the 'minimalist' treatment in Experiment A. Plots were mown at regular intervals to simulate grazing until two weeks before sowing when glyphosate was applied to the three replicate plots to be sown next. Adjacent plots were protected from the herbicide by plastic sheeting. Glyphosate was reapplied in the morning of the day of sowing. Shallow rows were prepared with a small pick, seed was evenly distributed and covered with a few millimetres of soil, which was pressed down by hand. Seed was sown in the first week of every month from June 1996 to May 1997. Seedlings were counted monthly for 12 months and, to assess long-term survival, again in early 1999 and mid– 2000. Plant heights were also measured at the last observation.

Survival data were reduced from the 2 species × 12 months-of-sowing treatment dimension by aggregating species and pairing consecutive months of sowing. Since maximum germinations varied noticeably between month-of-sowing pairs (8.7 to 30.2 seedlings/m), and given that interest was in relative survival rate rather than absolute survival numbers, data were expressed in units of percent survival (as a proportion of maximum germination). Results were summarised graphically by presenting average survival percentages, with variances of means indicated by s.e.m. error bars for only the combination (August/September 1996) so as to not clutter the graphic. Statistical analysis was not attempted due to the data exhibiting created means (forced 100% values), differing treatments at any one time point, and many zeros, especially at the later sowing times.

Experiment C: Growth and survival of eucalypt seedlings planted adjacent to native and exotic Plants

This experiment was carried out at the same site as Experiment B. Seedlings (*c.* 6 months old) of *Eucalyptus melliodora* were planted in paired microsites within the pasture after it had been mown to a height of *c.* 4 cm: (a) adjacent to a *Bothriochloa decipiens* plant and (b) within emerging or existing annual exotics. Seedlings were planted with as little disturbance to the soil and existing plants as was practicable. Plantings took place in May and September 1998 and, with some modifications, in April and September 1999. For the latter plantings, all extraneous perennials were removed prior to planting as follows. Native perennial grass microsites (i.e. *Bothriochloa decipiens* plants) were identified in March 1999, protected with an inverted bucket, and the area within a 1 m circle centred on the bucket sprayed with high concentration (20 mL/L water) glyphosate. Eucalypt seedlings were subsequently planted in pairs, the first adjacent to the *Bothriochloa decipiens* plant and the other *c.* 30 cm away in exotic annuals, in April and September 1999.

Forty to eighty seedlings were planted on each occasion. They were given a liberal application of water at planting and subsequently if considered necessary (Table 1). Following an acclimatisation period (when any pairs with one or more dead seedlings were excluded from further evaluation), seedling heights were measured from ground surface to uppermost green leaf at regular intervals for up to 12 months.

For each the four plantings, the statistical analysis considered pairs of seedlings as blocks and the two microsites as treatments in a randomised blocks design. Seedling height, change in seedling height between successive observations, and height change over the entire season for surviving seedlings were analysed using this framework as an unbalanced general linear model when one or both of the pair had died. Due to many seedling deaths during the series of experiments, some times of observation were not analysable due to lack of data. Although the pattern of seedling death in both microsites and in all plantings was similar, any differences in survival percentages at the final times of observation were analysed using generalised linear models.

Table 1. Conditions for *Eucalyptus melliodora* seedlings planted at Manildra in autumn and spring of 1988 and 1999.

	May 98	Sept. 98	April 99	Sept. 99
Seedbed preparation	Mowing prior to planting		Removal of extraneous perennial grasses with glyphosate in March 1999 & mowing prior to planting	
No. of seedling pairs planted	40	21	25	26
No. of follow-up irrigations	0	2	4	1
No. of seedling pairs after acclimatisation	32	18	8	25

Results

Experiment A: Success of direct drilled eucalypt seed in a Phalaris-*dominant pasture treated with herbicide up to one year previously*

Rainfall (Figure 1) was above average during germination and early establishment but was below average in the following autumn, winter and spring. However, during the second year (summer 1997/98 to spring 1998), rainfall was generally above average.

The proportion of live seed sown that produced seedlings at the time of maximum emergence was relatively low (2.2–6.4%). Levels of bare ground at emergence increased with the length of pre-sowing period of *Phalaris* control (r=0.9, n=5, *P*=0.04) but this did not affect numbers of emergents (Table 2).

Weeds, including young *Phalaris*, rapidly recolonised the plots and 1½ months after emergence, mean live herbaceous ('weed') cover in the treatments ranged from 45–65%. Seven months after eucalypt emergence, *Phalaris* was evident in all treatments, particularly those with the shortest period between initial spraying and sowing. At the last observation, 2¼ years after emergence, *Phalaris* was dominant in all treatments.

Seedling numbers declined in the first summer then stabilised until a crash in the population occurred in the second summer. Nett survival (i.e. seedling numbers at maximum emergence–deaths + delayed emergents) rates were similar in all treatments (Figure 2). The maximum total number of seedlings recorded across all replicates during the period of emergence (including those which emerged late) at the experimental site was 935. At one year of age, seedling numbers had declined to 213, a survival rate of 23% and of these only 34 (16%) survived the second summer, despite above average rainfall. By the last observation, at 2¼ years of age, only 17 contorted seedlings were present within the *Phalaris* stand.

Table 2. Herbaceous vegetative cover and numbers of eucalypts at Walli at emergence in October 1996.

Treatment: no. months between first herbicide application & sowing	Mean live cover (%)	Mean bare ground (%)	Mean no. of emergents/m
12	0.2	37.5	6.5
10	0.0	22.2	5.4
6	1.0	15.3	4.0
3	4.8	15.9	3.7
0	1.9	9.3	10.9
s.e.d.	0.9*	3.3	2.5

*calculated by excluding the mean with 0% live cover

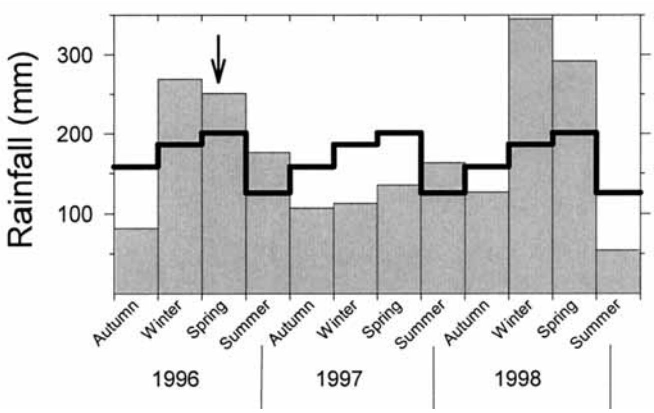

Fig. 1. Seasonal rainfall at 'Kentucky' (Bureau of Meteorology station no. 63234) during the eucalypt direct drilling experiment at Walli. Sowing time indicated by the arrow. The thickened line represents seasonal means.

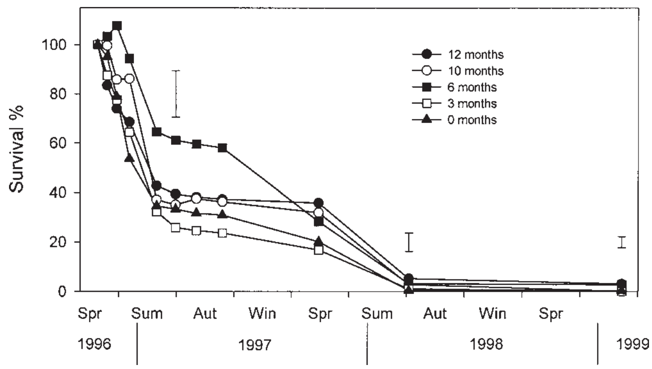

Fig. 2. Percentage nett survival of *Eucalyptus albens* seedlings in a re-establishing *Phalaris* pasture at Walli following direct drilling on 27 September 1996 into seedbeds prepared with one application of glyphosate at 12, 10, 6, 3 or 0 months prior to (and two applications just before) sowing. Reference datum is the average plant counts at the first observation on 28 October 1996 (see Table 2). Error bars are LSDs (P=0.05).

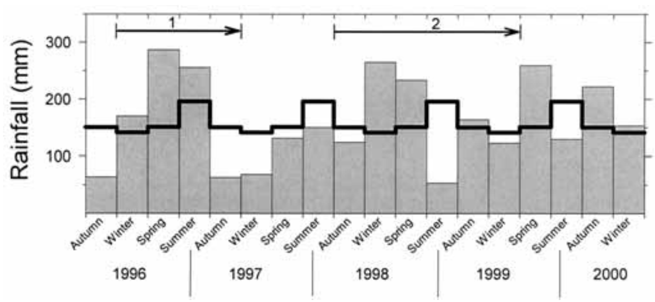

Fig. 3. Seasonal rainfall recorded at Manildra P.O. during the period of the eucalypt sowing and planting experiments. Thickened line represents long term seasonal means. Periods of monthly sowing of eucalypt seed, and of planting seedlings near exotic and native plants are represented by horizontal arrows 1 and 2 respectively.

Experiment B: Success of direct drilled eucalypt seed sown monthly in an exotic annual pasture

Rainfall was above average during the first nine sowings but was below average during the last three (autumn 1997) and in the subsequent winter (Figure 3). All sowings yielded seedlings. Maximum numbers ('maximum emergence', Figure 4 legend) were usually recorded one to two months after sowing except in March and April 1997 when there was insufficient rainfall for germination until May. In the latter case, seedlings emerged at the same time as those in the May sowing. Averaged across all sowings, the proportion of seedlings at maximum emergence was 10.1% (*Eucalyptus albens*) and 4.5% (*Eucalyptus melliodora*) of seed sown. Seed sown in December 1996 and February 1997 yielded the lowest proportions of emergents. Delayed emergence i.e. after maximum emergence, occurred following a number of sowings but numbers were generally low and were not included in the above calculations.

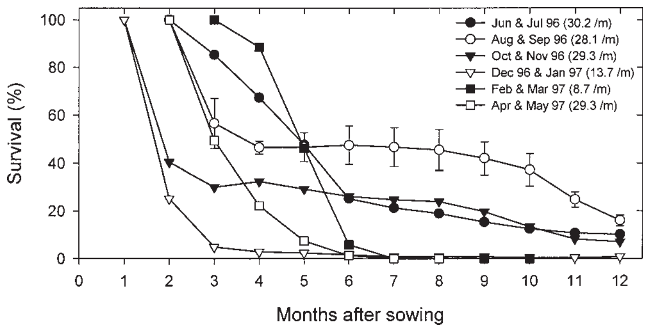

Fig. 4. Percentage nett survival of *E. albens* and *E. melliodora* seedlings in an exotic annual pasture at Manildra following direct drilling each month, June 1996 to May 1997, into seedbeds prepared with glyphosate. Sowing months have been amalgamated as pairs. Maximum seedling counts per month-pair shown in legend. Error bars are s.e.m.

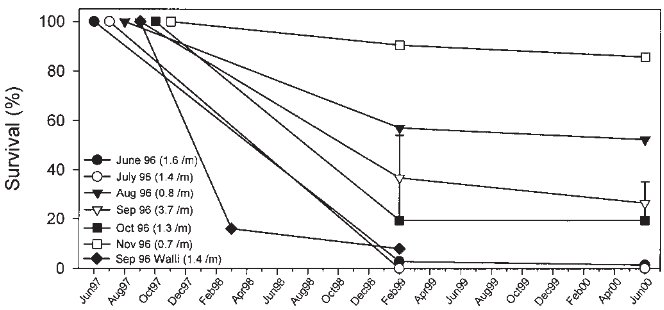

Fig. 5. Survival of one year old eucalypt seedlings from (a) sowings in different months in an exotic annual pasture at Manildra and (b) from the September 1996 sowing (aggregated across all treatments) in a re-establishing phalaris pasture at Walli. Maximum average seedling counts shown in legend. Error bars are s.e.m.

Virtually all seedlings from the summer and autumn (December 1996–May 1997) sowings were dead after one year (Figure 4), possibly reflecting below average rainfall following these sowings. Seedlings from the August/September 1996 period maintained the highest rate of survival during the first year of growth.

Figure 5 focuses on the survival of these seedlings once they reached one year of age. With one exception (a single survivor from the June 1996 sowing), all survivors present at June 2000 were from the August to November 1996 sowings. For comparison purposes, survival of one year old seedlings from the September 1996 sowing at Walli (experiment B) has been included in Figure 5. Although a critical measurement (late summer–early autumn 1998) is missing from the Manildra data, it appeared that the population crash in the second summer in the Walli *Phalaris* pasture, was less evident in the exotic annual pasture at Manildra, particularly for the August, September and November 1996 sowings.

At June 2000 the mean height of survivors from the August to November 1996 sowings was 89.6 cm, an average growth rate over c. $3^1/_2$ years of 25.6 cm/year.

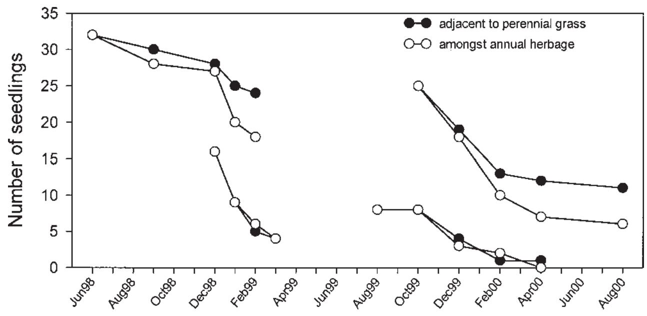

Fig. 6. Survival of acclimatised *E. melliodora* seedlings after plantings in two microsites at Manildra in autumn and spring of 1998 and 1999.

Experiment C: Growth and survival of eucalypt seedlings adjacent to native and exotic plants

With the exception of two dry summers, seasonal rainfalls were near or above average between planting and final measurements in August 2000 (Figure 4). However, rainfall from mid-autumn to early winter in 1999 was low and despite a number of follow-up irrigations, most of the original 50 seedlings planted in autumn 1999 died during the acclimatisation period (Table 1). Though many seedlings died during the dry summers, deaths were recorded in all seasons (Figure 6). Survival rates were low, particularly in the last three plantings (Table 3). The height of the pasture exceeded that of the eucalypt seedlings for much of the time, particularly in spring.

Growth rates of survivors ranged from c. 6 to 23 cm/y (Table 3). There were no significant differences in growth rates between seedlings adjacent to *Bothriochloa decipiens* and those amongst annual exotics during or at the end of the observation period in any of the plantings. However, for the autumn 1998 and spring 1999 plantings, final survival percentages were significantly ($P < 0.05$) lower for seedlings planted amongst annual exotics than for those adjacent to the native perennial grass.

Table 3. Growth and survival of eucalypt seedlings after plantings at Manildra in autumn and spring of 1998 and 1999. P = adjacent to a native perennial grass; A = amongst annual herbage.

	Autumn 98		Spring 98		Autumn 99		Spring 99	
	P	A	P	A	P	A	P	A
Survival (%)	75	56**	22	22	12	0	44	24**
Growth (cm/y)*	5.9	8.3	23.3	22.5	insufficient data		21.2	16.0

* Mean height increase of survivors from the end of the acclimatisation until the final observation (periods ranging from 4–10 months) expressed on an annual basis.

**Significant difference between microsites.

Discussion

Following successful emergence, eucalypt seedlings are subject to a range of hazards including herbivory, pathogens, competition from other plants and adverse climatic conditions.

These are inter-related as rainfall regime not only affects eucalypt seedlings directly but also indirectly through its effects on the abundance of herbivores and other plants. The latter factors can be manipulated to some extent e.g. by removing domestic herbivores and herbaceous competition at critical times to enhance regeneration (Whalley & Curtis 1991, Semple & Koen 1997, Lawrence et al. 1998).

If as data cited by Florence (1996, chapter 4) suggests, much of the eucalypt seedling's early growth in subhumid environments is allocated to root production, then seedlings are likely to be particularly susceptible to competition from plants which allocate more resources to top growth e.g. annual 'weeds'. Though this strategy may result in high losses of eucalypts, there is some evidence suggesting that once the eucalypt seedling is about one year old, its chance of survival is high. A number of observers (e.g. Curtis 1990, Dalton 1993, Colquhoun 2000) have reported that herbaceous competition affects survival during the eucalypt's first growing season; but in subsequent years it primarily affects growth.

Whether any one of the conditions affecting successful regeneration can be rated 'more important' than the others is doubtful as failure to satisfy any one condition at an appropriate time can lead to regeneration failure. In the experiments reported in this paper, conditions of seed supply, seed/soil contact and absence of large herbivores (and in the case of the planted seedlings, moisture supply during early growth) were satisfied. Climate and post-sowing herbaceous competition were not controlled though aspects of the composition of the latter were.

Most of the initial hypotheses were rejected:

1. Eucalypts could not be successfully established in a *Phalaris* pasture even where chemical control commenced one year before sowing. Levels of bare ground and live herbaceous cover were apparently favourable at eucalypt emergence; and survival of seedlings after one year (23%) was within expectations. However, only 8% of these survived to an age of 52 months, a much lower rate than was expected.
2. Survival of eucalypt seedlings after one year in a pasture dominated by annual exotics was highest following sowings in the months of June to November. After a further year, however, virtually all of the seedlings from the June and July sowings were dead. Though this tended to support the hypothesis that sowing in spring (August to November in this case) was the optimal sowing time for long-term survival, below-average rainfall following the summer and autumn sowings may have disadvantaged seedlings that emerged during this time.
3. There was no difference in the rate of growth between eucalypt seedlings planted beside a native perennial grass (*Bothriochloa decipiens*) and those planted within annual exotics. However, survival rate was enhanced by the perennial grass (or reduced by the exotics) in two of the four plantings.

The sowing experiments suggested that exotic pastures, whether dominated by annuals and/or perennials, were disadvantageous to the survival of young eucalypts. This is supported by previous experiments (e.g. Semple & Koen 1997, Lawrence et al. 1998) that showed that when exotic herbage competition was kept low for some time e.g. by scalping topsoil, eucalypt survival was enhanced.

Although there is some evidence that native pastures may be 'protective' of eucalypt seedlings (e.g. as reported by Noble 1980), this was a 'mechanical' effect that conceivably could also occur with tussocks of exotic grasses. Other evidence (e.g. Hitchmough et al. 1996) suggests that native grasses may be 'less competitive' than exotic pastures and this may have been the explanation for the high survival rate of one-year-old naturally-recruited seedlings in a native *Themeda* pasture reported by Semple and Koen (2001). This pasture was subjected to nil or infrequent 'crash grazing' and all eucalypt deaths were attributed to damage by sheep. Survival was high (91%) but mean growth rate from presumed time of emergence was low at 16.6 cm/y and attributed to pasture competition and harsh winters at an elevation of 860 m a.s.l. By contrast, eucalypts had low survival rates in the exotic annual pasture at Manildra but survivors achieved a mean growth rate of 25.6 cm/y from emergence to c. $3^1/_4$ years old.

The results of experiment C suggest that the single native grass plant may have conferred some benefit to eucalypt survival, though not growth. However, *Bothriochloa decipiens* was not dominant at the experimental site and consequently did not suppress cool-season annuals as was reported in *Bothriochloa*-dominant pastures by Moodie (1934) and in roadside eucalypt plantings by Colquhoun (2000). Planting eucalypt seedlings within a sward, rather than adjacent to just one plant of *Bothriochloa decipiens* may have yielded a more clear-cut result.

The exotic v. native status of the dominant pasture grasses is probably not the real issue; rather it is what occupies the spaces between the tussocks. In the highly modified woodland belt of south-eastern Australia, exotic annuals are abundant and, as noted by Prober (1996), they become more abundant towards the south. Though annuals compete for nutrients and moisture, their main effect on very young eucalypts is probably for light: 'smothering' by broad-leaved annuals (e.g. *Echium* and *Trifolium* spp.) during early growth and later on, by the collapse of erect grasses (e.g. *Lolium* and *Bromus* spp.) in late spring and early summer.

Although some eucalypts may escape this competition, it would be expected that those which emerged after cool-season annuals had died viz. in late spring or early summer, would have a higher chance of survival, albeit under hotter and drier conditions during early establishment. Limited support for this is provided by the time of sowing experiment and from documented cases of successful eucalypt regeneration following emergence in late spring and summer (Lawrence et al. 1998 Table 4).

If seedlings of an exotic perennial such as *Phalaris* are also present during the eucalypt's first year, it appears that the effect is little different to that of annuals: compare survival in the re-establishing *Phalaris* (and exotic annual) pasture in Figure 2 with that of the spring-sown eucalypts in the exotic annual pasture shown in Figure 4. Data from Figure 5 suggest that survival of the one year old seedlings from the spring 1996 sowing in the re-establishing *Phalaris* pasture was much lower than in the annual pasture. The presence of newly-established *Phalaris* plants at Walli was probably responsible for the sharp decline in numbers during summer 1997/98.

As far as eucalypt regeneration is concerned, the main difference between exotic and native pastures is probably the low levels or poor growth of exotic annuals in the latter. This in turn is probably related to soil fertility, either natural or induced e.g. by 'pasture improvement' or nutrient concentration by livestock. Landsberg et al. (1990) found significantly higher levels of available nitrogen in soils of grazed woodlands than in matched but essentially ungrazed stands with intact under-storey. Prober et al.'s (2002) study of intact and degraded under-storeys of grassy box woodlands found a strong association between soil nitrate and the dominance of robust exotics.

Grazing too is an important factor in eucalypt regeneration but its effects appear to be interactive with a range of factors such as fire, climatic conditions, spatial variation in nutrients (Clarke 2000) and pasture composition. Effects can be beneficial to emergence and early survival e.g. by selective removal of or prevention of seeding by annuals and/or creating bare ground. Young eucalypts can be killed by herbivores but at least some may survive in lightly grazed or crash-grazed native pastures.

It follows from these tentative suggestions that eucalypt regeneration is unlikely to occur where exotic perennials or annuals are abundant in the pasture. In the former case, scalping to remove existing plants and seed, or control by non-selective herbicides for a period in excess of one year, appears to be necessary. Residual herbicides such as simazine may also have a role, at least in the area adjacent to the eucalypts (Dalton 1993, Semple et al. 1995). These techniques are unlikely to be practical except over small areas such as strips, which are to be direct seeded or planted with tubestock.

Where annuals dominate or are abundant (e.g. in a native pasture), a number of possibilities present themselves: (1) preventing seeding by strategic crash-grazing or 'spray topping' (e.g. Burton 2002) in the year prior to seeding with eucalypts, (2) adopting normal agronomic procedures for growing a cereal crop; or in areas with particularly high fertility (3) depleting nutrients (and hence, subsequent growth of annuals) by growing and harvesting/grazing a high nutrient requirement crop such as sorghum.

In those native pastures where annuals contribute little to groundcover, all that may be necessary is the creation of bare ground by crash-grazing or burning prior to eucalypt seeding. The corollary to this is that in areas of native pasture where eucalypt regeneration is not required e.g. in pastoral areas of the *Eucalyptus populnea – Callitris glaucophylla* semi-arid woodlands, supplying seed of annuals (e.g. commercial varieties of *Trifolium* or *Medicago* species) and fertilisers may reduce the likelihood of eucalypt regeneration.

Conclusions

The results from the field studies described above and other work suggest that a major limitation to eucalypt regeneration in the woodland belt is the presence of exotic species in the pastures/ground-storeys of this highly modified region. In situations where annual exotics (or re-establishing exotic perennials) are abundant and actively growing, the effects of seedbeds prepared by knockdown herbicides, burning, slashing and/or grazing are short-lived. Competition for light and probably moisture by the herbaceous plants appears to be the main reason for low eucalypt survival during the first growing season. Eucalypt survival rates are generally higher in the second growing season except where newly-established exotic perennials (e.g. *Phalaris*) are present in which case survival would be expected to be very low.

The adverse effects of exotic annuals (predominantly cool-season types in southern areas) are ameliorated in low fertility situations and in relatively intact native pastures where they are less common. Where annuals are abundant, the young eucalypt can 'escape' their effects by emerging after they have 'hayed off' or following their removal (e.g. by herbicides) late in their growing season.

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